Fast Neutrons

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(Received February 28, 1938)

The distribution of fast neutrons about the Li+D source has been investigated by means of radioactivity induced in silver (24.5 min.) and aluminum (14.8 hr.). The observations are roughly in agreement with a distribution calculated from statistical considerations. The maximum neutron energy is 20.8 Mev. An increase in the deuteron energy results in an increase in the neutron energy as measured by the $n-3n$ reaction of scandium and the $n-2n$ reactions of silver and copper. The intermediate nucleus, Be^9, formed by the deuteron bombardment of lithium must have a life short compared to 10^{-12} sec. A number of materials when bombarded with high energy detuerons yield neutrons of sufficient energy to produce the $n-2n$ reaction in silver. Only the neutrons from lithium can produce the $n-3n$ reaction in scandium. Neutrons of somewhat less energy are required for the $n-2n$ copper reaction and of appreciably less for the $n-2n$ silver reaction. When scandium is bombarded with fast neutrons, reactions of the type $n-3n$, $n-2n$, $n-\alpha$, $n-p$ and $n-y$ take place in the following percentages, 24.0, 27.8, 20.6, <0.5, and 27.0, respectively.

Introduction

THE fast neutrons from the Li+D reaction have been used largely to discover new induced radioactive periods in the various elements. This use has been very successful and is of special interest because these neutrons are very proficient in the production of the $n-2n$ type of disintegration.[1, 2]

In this paper, however, known radioactive periods are used to indicate the distribution of these high energy neutrons about the lithium source, the dependence, if any, of the neutron energies on the bombarding deuteron energy and finally the potentialities of other fast neutron sources. Branching ratios for the disintegration products from scandium are also presented.

Fast Neutron Yield

The metallic lithium to be bombarded with deuterons was securely fastened upon a water cooled copper plate. Directly behind the copper plate was placed weighed samples of Cu, Sc, Ag, Al and Dy. These samples were all irradiated at the same time with neutrons obtained from bombarding the lithium with 5.7 Mev deuterons produced by the cyclotron at the University of Michigan. Other sets of samples were given similar treatments but with deuterons of lower energies. Aluminum foils were used to decrease the energy of the deuterons.

The intensities of radioactivity induced in four sets of samples are shown in Fig. 1. All the curves were arbitrarily put through the point 4 on the intensity scale. The rise in intensity of the dysprosium activity (strong 2.5-hr. slow neutron period) with increase of deuteron energy probably indicates the rise in the slow neutron background which, in turn, is a measure of the increase in the total number of Li+D disintegrations taking place. The rise in intensity in excess of the dysprosium rise would indicate the influence of the increased number of faster neutrons.

From the curves it is inferred that faster neutrons are required to produce the 10 min. period in copper than the 24.5 min. period in silver. Both periods are the result of an $n-2n$ type of reaction. The energy of neutrons required to produce the 4.0 hr. period in scandium, an $n-3n$ type of reaction,[3] is probably a little more than that required to produce the 10 min. copper period. Sagane reports that neutrons of more than 12 Mev are required to produce the 10 min. copper activity.[4] The 12.8-hr. copper activity which is produced by both fast and slow neutrons is shown and was measured from the same copper samples that gave the 10 min. period. The $n-\alpha$ type of reaction responsible for the 14.8-hr. period in aluminum apparently takes place as readily with neutrons of quite low energy as with those of much higher energy.

[1] M. L. Pool, J. M. Cork and R. L. Thornton, Phys. Rev. **52**, 239 (1937).
[2] F. A. Heyn, Physica **4**, 160 (1937).
[3] M. L. Pool, J. M. Cork and R. L. Thornton, Phys. Rev. **52**, 41 (1937).
[4] R. Sagane, Phys. Rev. **53**, 212 (1938).

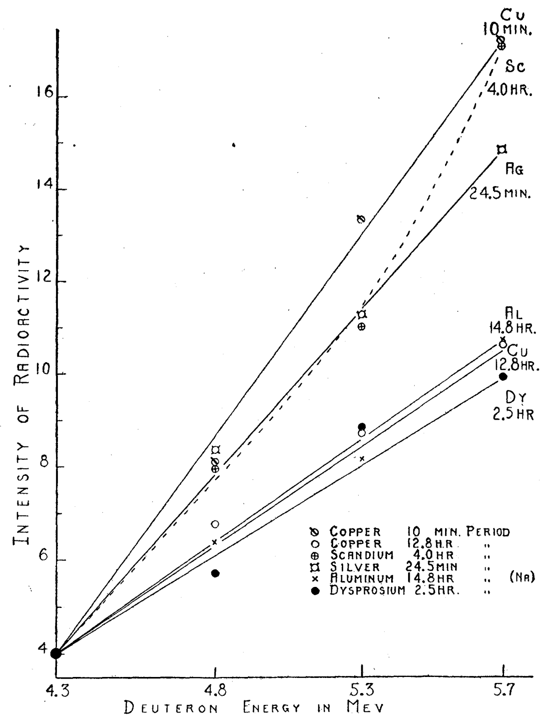

FIG. 1. Intensity of radioactivity induced by neutrons from the Li+D reaction *versus* energy of bombarding deuterons.

The extra energy acquired by the neutrons must be derived from the kinetic energy of the impinging deuterons. For this to happen it is necessary that the intermediate nucleus Be^9 at the time of its disintegration be in motion through the lithium metal. A 5.7 Mev deuteron gives a velocity of about 5×10^7 cm/sec. to Be^9. To bring this nucleus to rest in the metal a time of 10^{-11} to 10^{-12} sec. is required according to a simple calculation based upon estimated range-energy relations.[5] The life of Be^9 must therefore be short compared to 10^{-12} sec.

DISTRIBUTION OF FAST NEUTRONS

Strips of silver and aluminum 1 by 13 cm were bent in an arc of about 2.9 cm radius. The centers of the circular strips coincided with the region of the metallic lithium most strongly bombarded by deuterons of about 6 Mev. If the neutrons ejected from the lithium source had spherical symmetry in energy and number, then the radioactivity induced in each centimeter length of the 13 cm strips would be of the same intensity. The intensities however were found not to be the same. The asymmetry is shown by a polar plot in Fig. 2.

As may be seen the induced radioactivity in the direction of motion of the deuterons is definitely greater than in the direction at right angles and suggests therefore a marked forward throw of the neutrons resulting from the transmutation of the lithium. The 24.5-min. period of silver (Ag^{106}) and the 14.8-hr. period of aluminum (Na^{24}) are known to be produced by only fast neutrons and are not induced by slow neutrons or stray deuterons. Since the asymmetry of the silver radioactivity is greater than that of the aluminum it is concluded that the fast neutrons responsible for the production of the silver activity have a greater asymmetrical distribution than those responsible for the aluminum activity.

Inquiry may be made concerning what energy distribution might be expected of the transmutation products when the intermediate nucleus transforms according to

$$Li^7+D^2\rightarrow Be^9\rightarrow Be^8+n. \qquad (1)$$

Stephens using a 0.91 Mev deuteron beam obtained neutrons coming off at 90° which produced alpha-particle recoils in a helium filled cloud chamber.[6] His results are shown in Fig. 3 and may be interpreted as consistent with the above reaction. For a 6 Mev deuteron beam the

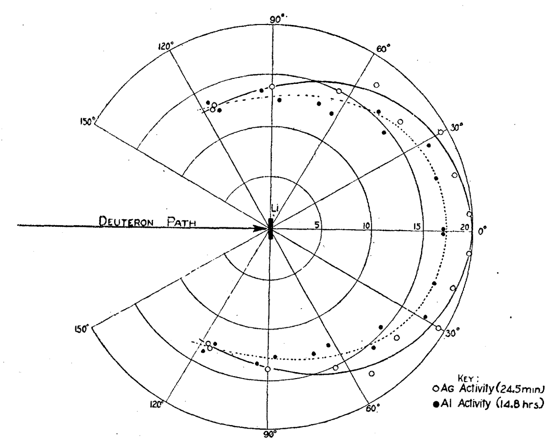

FIG. 2. Polar plot of intensities of radioactivity induced in samples of silver (Ag^{106}, 24.5 min.) and aluminum (Na^{24}, 14.8 hr.) placed symmetrically about the Li+D source of fast neutrons.

[5] F. Kirchner, H. Neuert and O. Laaff, Ann. d. Physik **30**, 527 (1937).

[6] W. E. Stephens, Phys. Rev. **53**, 223 (1938).

neutrons are calculated to be ejected in about equal numbers at right angles and in the forward direction with energies of 17.3 and 20.8 Mev respectively. Since fast neutrons over a wide range of energies seem about equally efficient in producing the $n-\alpha$ reaction in aluminum, the above-mentioned two groups of neutrons should induce in the aluminum approximately equal radioactivity, and give, therefore, a symmetrical intensity distribution. However, asymmetry is observed. This suggests that reaction (1) does not play the dominant role in this experiment.

The asymmetry is easily accounted for provided the transmutation takes place according to

$$Li^7+D^2 \rightarrow Be^9 \rightarrow He^4+He^4+n^1. \qquad (2)$$

For this type of reaction a statistical treatment of the neutron energy distribution may be made by assuming for the two alpha-particles and neutron, equal elements in phase space are equally probable. The treatment of this three-body problem is similar to that given by Fokker, Kloosterman and Belinfante on the energy distribution between the products of the transmutation of boron atoms into three alpha-particles.[7] In our problem it is of particular interest to calculate the number of neutrons, having energies between E and $E+dE$, that are ejected parallel $N_{0°}$ and at right angles $N_{90°}$ to the 6 Mev deuteron beam.

The results are expressed in the following equations where E is the energy of the neutron in Mev:

$$N_{0°}=(17.3+0.77E^{\frac{1}{2}}-E)(E)^{\frac{1}{2}},$$
$$N_{90°}=(17.3-E)(E)^{\frac{1}{2}}.$$

These equations are plotted in Fig. 3. The maximum energy expected for the forward neutrons is 20.8 Mev. The neutron distribution curve for zero energy deuteron bombardment is also shown and may be compared with the distribution observed by Bonner and Brubaker by means of proton recoils in a cloud chamber placed at right angles to an 0.85 Mev deuteron beam.[8] They observed that about 95 percent of the reactions were of type (2). The agreement between theory and experiment and between the experiments themselves is not good but some of

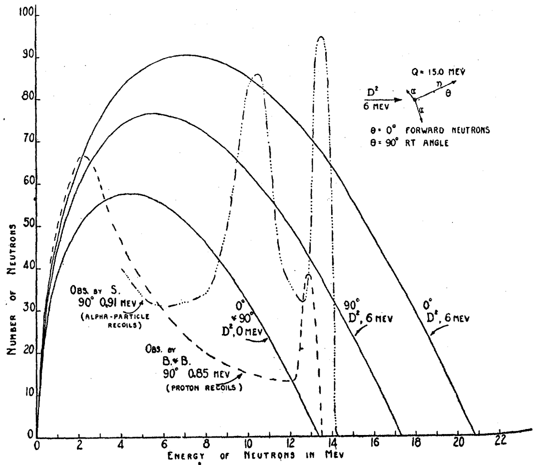

FIG. 3. Calculated energy distribution of neutrons in the directions parallel and at right angles to the impinging deuteron beam. Observations of Bonner and Brubaker (B and B) and Stephens (S) are also shown.

the discrepancy may be attributed to the uncertain cross section for high energy neutron interactions. It may be necessary also to introduce into the theoretical treatment, factors other than those of pure chance as has already been suggested by Cockcroft and Lewis[9] in connection with the break up of B^{10}.

The ratio of the calculated total number of forward neutrons to the total number of right angle neutrons is 1.8. The observed ratios of the intensity of the radioactivity in silver and aluminum in these two directions are 1.43 and 1.35, respectively. The observed asymmetry in the intensity of the radioactivity is therefore easily accounted for on the hypothesis of type (2) reaction.

OTHER FAST NEUTRON SOURCES

A number of materials were bombarded with 6.3 Mev deuterons and the intensities of the fast neutron induced radioactive periods in Ag, Cu, Al and Sc were measured. Table I summarizes the results.

As is seen the Li+D reaction furnishes the best source of fast neutrons. Again the $n-3n$ reaction in scandium appears to require more energetic neutrons than does the $n-2n$ reaction in copper. The $n-2n$ reaction in silver is next in

[7] A. D. Fokker, H. D. Kloosterman and F. J. Belinfante, Physica 1, 705 (1934).

[8] T. W. Bonner and W. M. Brubaker, Phys. Rev. 48, 742 (1935).

[9] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. 154, 254 (1936).

TABLE I. *Intensities of radioactivities induced by neutrons from various sources.*

Neutrons from	24.5 min. Ag $n-2n$	10 min. Cu $n-2n$	5 min. Cu $n-y$	14.8 hr. Al $n-\alpha$	4 hr. Sc $n-3n$
Li+D	100	100	—	57.5	100
B+D	11.5	12	66	100	—
CaF_2+D	3.15	—	71	59.5	—
Ag+D	2.15	—	20	38	—
Fe+D	1.9	—	12	44	—
Al+D	1.75	—	22	73	—
Be+D	—	—	100	57.5	—

order and the $n-\alpha$ reaction in aluminum requires the least energy.

The maximum energy of the neutrons in the forward direction from the Be+D reaction is calculated to be about 10 Mev. Since the $n-2n$ reaction in silver does not take place with these neutrons, it is inferred that more than 10 Mev neutrons are required to remove two neutrons from silver. There must, however, be neutrons with energies greater than this value released from Al, Fe, Ag, CaF_2 and B when they are bombarded by 6.3 Mev deuterons. It is interesting to note that neutrons from the B+D reaction seem very efficient in producing the $n-\alpha$ reaction in aluminum.

It is also interesting that deuteron bombardment of aluminum produces neutrons which are energetic enough to then produce quite strongly the $n-\alpha$ reaction in aluminum. This tandem reaction probably accounts for at least some of the long radioactive periods observed in aluminum when given extensive bombardment with high energy deuterons.[10] Likewise, neutrons from the Ag+D reaction are capable of producing, although weakly, the $n-2n$ type of reaction in silver.

Branching Ratios

Since an appreciable quantity of scandium was used in the above experiments, six samples that showed strong radioactivity were chosen to be observed over a period of a few months for the purpose of calculating the branching ratios or relative rates of formation of the disintegration products. Two of the samples were followed in their chemical separations (K, Ca, Sc). The samples had been irradiated from one to four hours with neutrons from a lithium target bombarded with about 6.0 μA of 6.3 Mev deuterons.

[10] M. L. Pool and J. M. Cork, Phys. Rev. **51**, 383 (1937).

TABLE II. *Percent of various radioactive nuclei formed in the transmutation of* Sc^{45} and V^{51} *when bombarded by high energy neutrons.*

Nucleus Bombarded	Type of Reaction	Nucleus Formed	Radioactive Period	% of Such Nuclei Formed
$_{21}Sc^{45}$	$n-3n$	Sc^{43}	4.0 hr.	24.0
	$n-2n$	Sc^{44}	52 hr.	27.8
	$n-\alpha$	K^{42}	12.4 hr.	20.6
	$n-p$	Ca^{45}	2.4 hr.	< 0.5
	$n-y$	Sc^{46}	85 da.	27.0
$_{23}V^{51}$	$n-3n$	V^{49}	33 min.	0
	$n-2n$	V^{50}	3.7 hr.	3
	$n-\alpha$	Sc^{48}	41 hr.	32
	$n-p$	Ti^{51}	2.8 min.	65

Table II shows a summary of the results and expresses in the last column the relative rates of formation of the various radioactive transmutation products as the percent of such nuclei formed. It is noticed that scandium is transmuted most of the time according to the $n-2n$ type of reaction. The $n-p$ reaction is very weak which is consistent with the findings of Walke.[11] However, his observations that the number of $n-3n$ reactions is nearly twice that of the $n-2n$ reactions is not confirmed. As observed from the six samples in this research the ratio of the number of the former reactions to the latter is more nearly 6/7.

It was thought that possibly the branching ratios for the neighboring odd nucleus $_{23}V^{51}$ would be similar to those for $_{21}Sc^{45}$. Tentative values were obtained and are shown also in Table II. As may be seen, no similarity is apparent.

Acknowledgments

The author is very grateful to Professor J. M. Cork and Dr. R. L. Thornton of the University of Michigan for the opportunity of working in their laboratory with the cyclotron. Professor B. S. Hopkins of the department of chemistry at the University of Illinois kindly loaned the author a quantity of his dysprosium that is of high purity. Professor Quill of the department of chemistry at Ohio State University supplied the large quantity of scandium used. Professor L. H. Thomas suggested using the statistical treatment for the energy distribution of the neutrons. The author is also grateful to have been the recipient of the Elizabeth Clay Howald Scholarship for 1936–37.

[11] Harold Walke, Phys. Rev. **52**, 669 (1937).